The Boötes Void: Investigating the Formation and Evolution of Large-Scale Cosmic Voids in the Universe

Charvi Handa[1], Raghu Raja Mehra[2]

Abstract: ***The universe is not filled evenly with matter. On the largest scales it resembles a foam or a web, in which luminous galaxies gather along filaments and sheets while enormous, nearly empty regions occupy most of the volume. The largest of these regions are called cosmic voids, and among the best known is the Boötes Void a roughly spherical region about 330 million light-years across, discovered in 1981, that contains only a small fraction of the galaxies expected for its size. This paper reviews what is currently understood about such structures. It begins with the architecture of the cosmic web and the discovery of the Boötes Void, then examines the internal density structure of voids, the physical processes that create them from tiny primordial density fluctuations, and the way they grow, merge and stabilise across cosmic time. The paper then discusses why voids have become valuable cosmological laboratories: because they are dominated by dark energy rather than by gravity, they offer unusually clean tests of the expansion history of the universe and of the theory of gravity itself. Observational methods, major surveys and outstanding puzzles - including the CMB Cold Spot and the possibility that our own galaxy sits inside a large under-density - are also reviewed. Throughout, the paper distinguishes carefully between well-established observation, widely accepted theory and open speculation, and closes with recommendations for future work.***

Keywords: Boötes Void, cosmic voids, large-scale structure, cosmic web, dark energy, galaxy surveys, structure formation, cosmology

1. Introduction

For most of recorded history, the night sky appeared to be scattered with stars in no particular order. The twentieth century changed that picture completely. As telescopes improved and astronomers began measuring not only the positions of galaxies but also their distances, a striking pattern emerged: galaxies are not distributed randomly through space. They cluster into groups, groups gather into clusters, and clusters string themselves together into vast filaments and sheets. Between these bright structures lie enormous regions that are almost, but not entirely, empty.
This arrangement is now called the cosmic web, and it is one of the most important discoveries in modern cosmology. It matters because the pattern is not decorative. The shape of the cosmic web is a direct record of how the universe began, what it is made of, and how gravity has shaped it over almost fourteen billion years. The empty regions of the web - the cosmic voids - carry as much information as the bright regions, and in some respects they carry cleaner information, because less has happened inside them.

The Boötes Void, sometimes called the Great Void or the Supervoid, is the most famous single example. Discovered in 1981 by Robert Kirshner and colleagues during a redshift survey, it is a roughly spherical region approximately 330 million light-years in diameter, lying some 700 million light-years from Earth in the direction of the constellation Boötes. If galaxies were distributed evenly, a region of that size should contain roughly two thousand galaxies. Careful searching has found only around sixty. The void is therefore not truly empty, but it is dramatically underpopulated.

This paper examines what such a structure is, how it formed, how it has changed over time, and what it can teach us. Section 2 describes the large-scale structure of the universe and where voids fit within it. Section 3 sets out the discovery and measured properties of the Boötes Void. Section 4 examines the internal density structure that all voids share. Sections 5 and 6 turn to theory: how voids form from almost imperceptible ripples in the early universe, and how they evolve, merge and eventually stabilise. Section 7 discusses the use of voids as cosmological laboratories. Section 8 reviews observational methods and surveys, Section 9 outlines unresolved puzzles, and Sections 10 and 11 discuss limitations and conclusions. The aim is a clear, evidence-based account suitable for a reader who is comfortable with physics but not necessarily with advanced mathematics.

2. The Large-Scale Structure of the Universe

To understand a void, one must first understand what it is a void in. Zooming outward from the Earth, structure appears at every scale. Planets orbit stars; stars gather into galaxies; galaxies bind into groups such as our own Local Group; groups fall into clusters containing hundreds or thousands of galaxies; and clusters themselves are strung along superclusters. Above this level, at scales of hundreds of millions of light-years, the pattern finally becomes recognisable as a web.

The components of the cosmic web are usually described in four categories. Clusters, or nodes, are the densest points, where filaments intersect. Filaments are long, thread-like chains of galaxies connecting the nodes. Walls, or sheets, are flattened structures that stretch between filaments. Voids are the large, roughly rounded regions of low density enclosed by all of the above. Together these form a structure often compared to a sponge or to soap bubbles, in which the visible matter forms the surfaces and the voids form the interiors.

The proportions are counter-intuitive. Voids occupy the overwhelming majority of the volume of the universe -

commonly estimated at seventy to eighty per cent - while containing only a small minority of its galaxies. Most of the visible universe, by volume, is emptiness. Figure 5 illustrates this contrast between the share of volume and the share of galaxies. This is not an accident of measurement; it is a natural consequence of the way gravity redistributes matter, as Section 5 explains.

It is also important to be precise about what "empty" means. A cosmic void is not a vacuum in the laboratory sense. It contains diffuse gas, dark matter, a scattering of isolated galaxies and the same background radiation that fills the rest of space. What it lacks is concentration. Typical void densities are around one-tenth to one-fifth of the mean density of the universe, and in the deepest interiors the figure can fall lower still.

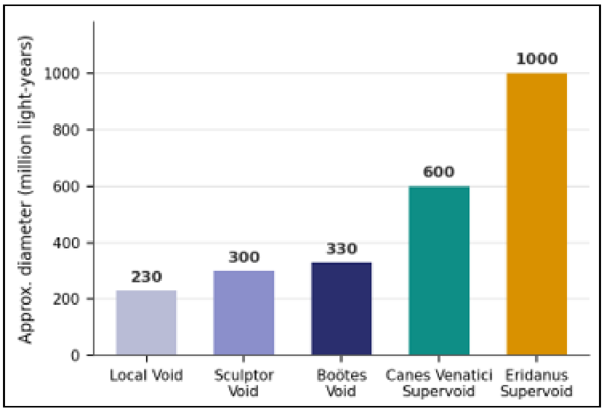

Figure 1: Approximate diameters of well-known cosmic voids (illustrative comparison).

3. Discovery and Properties of the Boötes Void

The Boötes Void was found almost by accident. In the late 1970s, astronomers at the Harvard–Smithsonian Center for Astrophysics were conducting redshift surveys measuring how much the light of a galaxy is stretched towards the red end of the spectrum, which indicates how fast it is receding and therefore how far away it lies. Building a three-dimensional map in this way was slow work, but it revealed something no two-dimensional photograph could: gaps.

In 1981, Kirshner, Oemler, Schechter and Shectman reported an unusually large gap in the direction of Boötes. Their survey had targeted several separate fields, and the same range of distances was empty in all of them, which indicated a single connected structure rather than a few unrelated blank patches. The scale was unprecedented for the time, and the result was initially met with scepticism. Subsequent surveys, however, confirmed both the existence and the approximate dimensions of the region.

Table I summarises the principal measured and estimated properties of the void. The values should be treated as approximate: different surveys define void boundaries differently, and published diameters range from roughly 250 to 330 million light-years depending on the criterion used.

Table I: Principal Properties of the Boötes Void

Property	Approximate value
Discovered	1981, Kirshner et al.
Constellation	Boötes (northern sky)
Distance from Earth	≈ 700 million light-years
Diameter	≈ 330 million light-years
Volume share of sky region	≈ 0.27% of observable volume
Galaxies observed	≈ 60
Galaxies expected if average	≈ 2000
Relative density	≈ 10–20% of cosmic mean

Two features of the table deserve comment. The first is the gap between the observed and expected galaxy counts, which is the reason the void attracted attention at all. The second is that the void is not featureless. The galaxies that do lie within it are not scattered at random; several appear to form a rough tube or chain running through the interior. This is consistent with the idea, discussed in Section 6, that the Boötes Void is not a single original structure but the merged product of several smaller voids, with the surviving galaxies tracing the remnants of the walls that once separated them.

It is also worth noting that the Boötes Void is large but not unique, and not the largest known. Figure 1 compares it with other well-studied underdense regions. The Local Void, which begins near the edge of our own Local Group, is smaller but far closer. The Eridanus Supervoid, associated with an unusual cold region in the cosmic microwave background, may be substantially larger. The Boötes Void's fame owes as much to its early discovery and its striking emptiness as to its absolute size.

4. The Internal Structure of Voids

Voids are not uniform inside. If one measures galaxy density as a function of distance from the centre of a typical void, a characteristic profile emerges, shown in Figure 2. Density is lowest at the centre, rises gradually through the interior, climbs steeply near the boundary, and overshoots the cosmic average in a compressed shell- the void wall- before settling back towards the mean in the surrounding filaments.

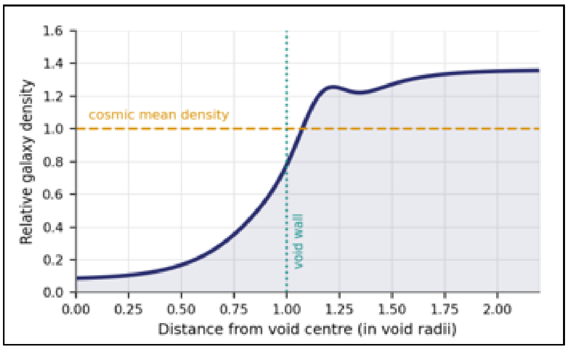

Figure 2: Typical density profile of a cosmic void from centre to wall (illustrative)

This profile is a physical signature, not a coincidence. It reflects the fact that matter has been evacuated from the interior and deposited at the edges. The overdense ridge at the boundary is made of material that was once inside the void and has since migrated outward. In this sense, voids and the structures around them are two halves of a single process: walls exist because voids emptied.

The galaxies that remain inside voids are also distinctive. Void galaxies tend to be smaller, bluer and richer in gas than galaxies of similar mass in dense environments, and they typically continue forming stars for longer. The reason is environmental. In clusters, galaxies interact frequently, strip one another of gas and are exposed to hot intracluster material that suppresses star formation. In voids, encounters are rare, gas reservoirs survive, and evolution proceeds slowly and undisturbed. Void galaxies are therefore sometimes described as cosmic late developers, and they offer a useful control sample for studying how environment shapes galaxy evolution.

Smaller substructures known as void-in-void configurations are also observed: internal ridges and sub-voids that have not yet fully merged. The chain of galaxies observed within the Boötes Void is generally interpreted in this way.

5. The Formation of Cosmic Voids

The origin of voids lies in the earliest moments of the universe. According to the standard cosmological model, the very early universe was almost perfectly smooth, but not exactly so. Quantum fluctuations during a brief period of rapid expansion, known as inflation, left tiny variations in density differences of roughly one part in one hundred thousand. These variations are directly observed today as temperature ripples in the cosmic microwave background, the relic radiation released when the universe first became transparent.

Those ripples are the seeds of everything. Regions that began slightly denser than average had slightly stronger gravity, so they attracted more matter, became denser still, and eventually collapsed into the galaxies and clusters we see. Regions that began slightly less dense had slightly weaker gravity than their surroundings and therefore lost matter to them. Over billions of years, this feedback amplified a whisper of a difference into the dramatic contrast of the modern cosmic web.

The essential mechanism is often described as effective repulsion. An underdense region does not push matter away in any literal sense; rather, the surrounding denser regions pull matter outward more strongly than the interior pulls it inward. Relative to the average expansion of the universe, matter therefore drains out of the void and accumulates in its walls. The void itself expands faster than the universe as a whole, which is why voids grow both in absolute size and as a fraction of total volume.

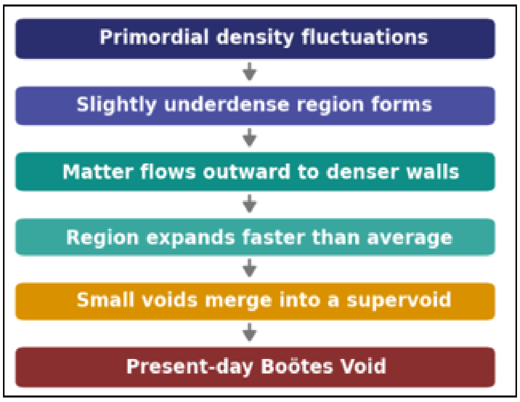

Figure 3: Formation pathway of a supervoid from primordial fluctuations to the present day.

Figure 3 summarises this sequence. It is worth emphasising how modest the starting point is. A region that began just a fraction of a per cent below average density is sufficient, given sufficient time, to become a region hundreds of millions of light-years across containing a twentieth of the expected number of galaxies. The cosmic web is an amplifier of very small beginnings.

Two further refinements are important. The first, known as the void-in-cloud process, describes small voids that form inside larger overdense regions; these are eventually squeezed out of existence as the surrounding region collapses. The second, the void-in-void process, describes small voids forming within larger underdense regions; these survive and merge, and it is this pathway that produces supervoids. The distinction explains why the void population is dominated by a modest number of very large structures rather than by an enormous number of small ones.

6. Evolution and Growth Across Cosmic Time

Voids are not static. They have a history, and their present configuration is a snapshot of an ongoing process. Three stages can usefully be distinguished: growth, merging and freeze-out.

During the growth stage, which begins once matter and radiation decouple and gravity can act freely, an underdense region expands relative to its surroundings while shedding matter into its boundary. The rate of expansion depends on the initial depth of the underdensity and on the overall expansion rate of the universe. Figure 4 shows an illustrative comparison of how voids of different initial scale grow over cosmic time.

Paper ID: SR26831173015 DOI: https://dx.doi.org/10.21275/SR26831173015

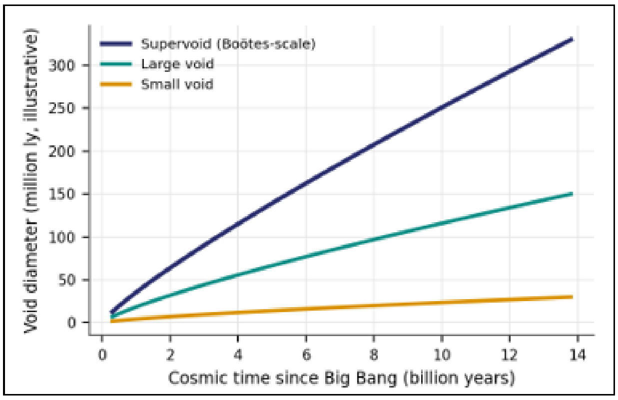

Figure 4: Illustrative growth of voids of different scales over cosmic time

During the merging stage, neighbouring voids grow until the thin walls between them can no longer be sustained. As matter drains away from a wall in both directions, the wall thins, fragments, and finally collapses into a chain of galaxies or dissolves entirely. The two voids then behave as one. This process repeats hierarchically, so that a present-day supervoid is best understood as the accumulated result of many earlier mergers rather than as a single expanded bubble. The observed internal galaxy chain in the Boötes Void is the kind of remnant this process would leave behind.

The freeze-out stage is more recent and depends on dark energy. Since the universe began accelerating its expansion roughly five to six billion years ago, the growth of structure has slowed. Gravity's ability to pull matter into new concentrations is progressively weakened as space expands more rapidly, and the pattern of the cosmic web becomes increasingly fixed. Voids continue to enlarge because space itself is expanding, but their contrast with their surroundings changes more slowly than it once did. In broad terms, the era of dramatic structure formation is behind us.

One consequence is that the void population itself is a cosmological clock. The number, size distribution and shape of voids at different distances and therefore at different times in cosmic history depend on how quickly structure has grown, which in turn depends on the amounts of matter and dark energy present. Comparing observed void populations at different epochs is thus a way of measuring the expansion history of the universe.

7. Voids as Cosmological Laboratories

For several decades, voids were treated mainly as the gaps between the interesting parts of the universe. That view has changed. Voids are now recognised as some of the most informative regions available, for three related reasons.

First, voids are simple. In dense environments, the behaviour of matter is complicated by shock heating, star formation, supernova feedback, active galactic nuclei and repeated mergers. These processes are difficult to model and introduce large uncertainties. Inside voids, almost none of them operate strongly. The dominant physics is gravity and expansion, both of which are well understood, so predictions can be compared with observation more directly.

Second, voids are dark-energy dominated. Because their matter content is low, the repulsive influence of dark energy is proportionally more important inside voids than anywhere else. Any deviation from the standard model of dark energy, or any modification to the law of gravity on large scales, should show up in void properties- their sizes, shapes, growth rates and the density profiles of their walls more clearly than in dense regions, where strong local gravity masks such effects. Several proposed modified-gravity theories predict measurably different void statistics from standard general relativity.

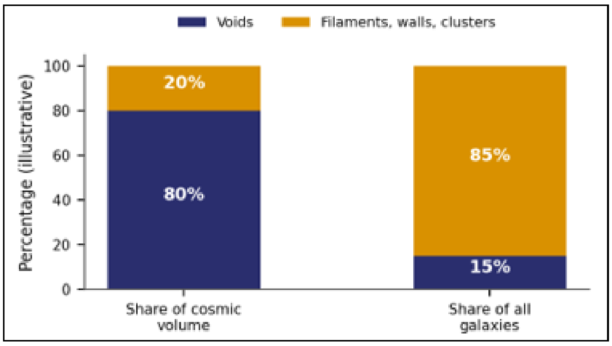

Figure 5: Share of cosmic volume compared with share of galaxies (illustrative).

Third, voids leave a measurable imprint on the cosmic microwave background through the integrated Sachs–Wolfe effect. A photon falling into a large underdense region gains a small amount of energy, then loses slightly more when climbing out, because the void has expanded during the crossing. The result is a faint cooling of the radiation seen through large voids. Detecting this effect is difficult and the measurements remain debated, but its existence is a prediction of an accelerating universe and therefore an independent test of dark energy.

A further application uses the shapes of voids. On average, voids should be spherical; if the assumed relationship between redshift and distance is wrong, they will appear systematically stretched or squashed along the line of sight. Measuring this distortion a version of the Alcock–Paczyński test provides a geometric handle on the expansion history that does not depend on knowing the intrinsic brightness of any object.

8. Observational Methods and Major Surveys

Mapping emptiness is harder than mapping objects, because a void must be inferred from the absence of detections rather than from a direct signal. The primary method remains the redshift survey: measure the spectra of very large numbers of galaxies, convert redshift to distance, build a three-dimensional map, and identify regions where the density falls below a defined threshold. Different void-finding algorithms use different thresholds and different definitions of the boundary, which is the main reason published void catalogues disagree about sizes and counts.

Table II: Major Surveys Relevant to Void Research

Survey	Contribution
CfA Redshift Survey	First large 3-D maps; Boötes Void and Great Wall
2dF Galaxy Redshift Survey	Statistical void catalogues from ~220,000 galaxies
Sloan Digital Sky Survey	Detailed void catalogues over a wide sky area
Dark Energy Survey	Void lensing and ISW measurements
DESI	Millions of spectra; void statistics across cosmic time
Euclid	Wide-field imaging and weak lensing of voids

Two complementary techniques deserve mention. Weak gravitational lensing measures the very slight distortion of the images of distant galaxies caused by the mass distribution in front of them. Because voids are underdense, they defocus rather than focus light, producing a characteristic negative lensing signal that can be used to weigh a void without assuming that galaxies trace mass faithfully. Absorption-line studies use the light of distant quasars as a probe: as the light passes through intervening gas, it acquires absorption features that reveal material too faint to be seen directly. This is how astronomers verify that voids contain diffuse gas even where no galaxies are visible.

Simulations form the third pillar of the field. Large cosmological simulations follow the gravitational evolution of billions of particles from near-uniform initial conditions to the present, and reliably reproduce the observed web of filaments, walls and voids. Agreement between simulated and observed void populations is one of the stronger pieces of evidence supporting the standard cosmological model.

9. Open Questions and Anomalies

Several questions about voids remain genuinely unsettled, and it is important for a review of this kind to state them plainly rather than to present the field as closed.

The first concerns definition. There is no universally agreed criterion for where a void begins and ends, and reported statistics depend on the algorithm used. This complicates comparisons between studies and weakens some cosmological constraints derived from void catalogues.

The second concerns the CMB Cold Spot, an unusually cool region in the cosmic microwave background. One proposed explanation is a very large foreground supervoid in the direction of Eridanus, acting through the integrated Sachs–Wolfe effect. Surveys have found an underdensity in roughly the right place, but most analyses conclude that it is not deep enough to account for the full temperature deficit. The anomaly remains unexplained, and alternative interpretations, including statistical fluctuation, are still viable.

The third concerns our own position. Some studies suggest that the Milky Way lies within a large-scale underdensity, occasionally called the KBC void, extending for a billion light-years or more. If correct, this would have practical consequences: a local underdensity would slightly bias measurements of the local expansion rate, and has been proposed as a partial contribution to the persistent disagreement between different measurements of the Hubble constant. The evidence is contested, with different tracers giving different answers, and the proposal should be regarded as an open hypothesis rather than an established result.

Fourth, the largest observed structures- both the largest voids and the largest galaxy groupings - sit uncomfortably close to the scale at which the universe is expected to become statistically uniform. Whether these structures are genuine challenges to the assumption of large-scale homogeneity, or whether they are the kind of rare fluctuation any random field will occasionally produce, remains an active debate.

10. Discussion and Limitations

The account presented here rests on a body of evidence that is strong in outline and uneven in detail. The existence of voids, their approximate sizes, their density profiles and their broad formation mechanism are supported by multiple independent lines of evidence: redshift surveys, lensing measurements, absorption studies and numerical simulations all agree. These conclusions can be stated with reasonable confidence.

Other statements are more provisional. Precise diameters depend on definitions. Density estimates depend on assumptions about how faithfully visible galaxies trace invisible dark matter, and void interiors may contain faint galaxies that current instruments cannot detect, which would raise measured densities. Claims about the Cold Spot, the local underdensity and modified gravity are all currently contested. The numerical values in the figures of this paper are illustrative and are intended to convey relationships and orders of magnitude, not measured results; readers seeking precise figures should consult the primary literature cited.

A general caution also applies. Because voids are defined by absence, selection effects are unusually important. A survey that is not deep enough will systematically find voids where there are merely faint galaxies. Distinguishing genuine emptiness from incomplete observation is the central methodological difficulty of the field, and progress has depended as much on improved survey completeness as on improved theory.

11. Conclusion and Future Scope

The Boötes Void is a useful entry point into one of the largest questions in cosmology: why the universe has the structure it has. A region three hundred million light-years across, containing a small fraction of the galaxies it should, is not an oddity to be explained away. It is the expected outcome of a process that begins with almost imperceptible variations in the density of the early universe and is amplified by gravity across billions of years into the cosmic web observed today.

The review supports three main conclusions. First, voids are a structural necessity rather than an anomaly: matter drawn into filaments and clusters must be drawn out of somewhere, and voids are that somewhere. Second, voids evolve, growing and merging over cosmic time and slowing as dark energy comes to dominate, so that the void population functions as a record of the expansion history. Third, voids are scientifically valuable precisely because they are simple, offering some of the cleanest available tests of dark energy and of gravity on the largest scales.

Future progress is likely to come from three directions. Deeper spectroscopic surveys, particularly DESI and Euclid, will produce void catalogues large enough to reduce statistical uncertainty substantially and to track void populations across a wide range of cosmic epochs. Improved and standardised void-finding methods would allow results from different studies to be compared meaningfully. Finally, targeted study of void galaxies with next-generation telescopes will test whether galaxy evolution in near-isolation follows the same rules as in dense environments. Taken together, these developments should turn the emptiest parts of the universe into some of its most informative.

References

[1] R. P. Kirshner, A. Oemler, P. L. Schechter and S. A. Shectman, "A million cubic megaparsec void in Boötes," The Astrophysical Journal Letters, vol. 248, pp. L57–L60, 1981.
[2] R. van de Weygaert and E. Platen, "Cosmic voids: structure, dynamics and galaxies," International Journal of Modern Physics: Conference Series, vol. 1, pp. 41–66, 2011.
[3] S. F. Shandarin, "Cosmic web, multi-stream flows and tessellations," Journal of Cosmology and Astroparticle Physics, vol. 5, 015, 2011.
[4] P. J. E. Peebles, "The void phenomenon," The Astrophysical Journal, vol. 557, pp. 495–504, 2001.
[5] N. Hamaus, P. M. Sutter and B. D. Wandelt, "Universal density profile for cosmic voids," Physical Review Letters, vol. 112, 251302, 2014.
[6] J. M. Colberg et al., "The Aspen–Amsterdam void finder comparison project," Monthly Notices of the Royal Astronomical Society, vol. 387, pp. 933–944, 2008.
[7] I. Szapudi et al., "Detection of a supervoid aligned with the cold spot of the cosmic microwave background," Monthly Notices of the Royal Astronomical Society, vol. 450, pp. 288–294, 2015.
[8] R. C. Keenan, A. J. Barger and L. L. Cowie, "Evidence for a ~300 Mpc scale under-density in the local galaxy distribution," The Astrophysical Journal, vol. 775, 62, 2013.
[9] M. C. Neyrinck, "ZOBOV: a parameter-free void-finding algorithm," Monthly Notices of the Royal Astronomical Society, vol. 386, pp. 2101–2109, 2008.
[10] Planck Collaboration, "Planck 2018 results VI: Cosmological parameters," Astronomy & Astrophysics, vol. 641, A6, 2020.